Horizontal Branch Stars and the Ultraviolet Universe

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Summary. Extremely hot horizontal branch (HB) stars and their progeny are widely considered to be responsible for the "ultraviolet upturn" (or UVX) phenomenon observed in elliptical galaxies and the bulges of spirals. Yet, the precise evolutionary channels that lead to the production of these stars remain the source of much debate. In this review, we discuss two key physical ingredients that are required in order for reliable quantitative models of the UV output of stellar populations to be computed, namely, the mass loss rates of red giant branch stars and the helium enrichment "law" at high metallicities. In particular, the recent evidence pointing towards a strong enhancement in the abundances of the α-elements in the Galactic bulge (compared to the disk), and also the available indications of a similar overabundance in (massive) elliptical galaxies, strongly suggest that the helium abundance Y may be higher in ellipticals and bulges than it is in spiral disks by an amount that may reach up to 0.15 at [Fe/H] $\sim +0.5$. If so, this would strongly favor the production of hot HB stars at high metallicity in galactic spheroids. We also discuss the existence of mass loss recipes beyond the commonly adopted Reimers "law" that are not only more consistent with the available empirical data, but also much more favorable to the production of extended HB stars at high metallicity. Finally, we discuss new empirical evidence that suggests that different evolutionary channels may be responsible for the production of EHB stars in the field and in clusters.

1 Introduction

Horizontal branch (HB) stars are the immediate progeny of low-mass red giant branch (RGB) stars. They appear to have been discovered by [84] in an analysis of data collected by [82] for the globular cluster M3 (NGC 5272), and were first correctly identified as stars that burn helium in their cores and hydrogen in a shell by [41]. Recent reviews dealing with the general properties and astrophysical importance of these stars have been provided in [58, 17], whereas a recent overview of low-mass stellar evolution can be found in [16].

For a given chemical composition, and after losing mass on the RGB, such stars end up at different positions along the zero-age HB (ZAHB), de-

pending on the total amount of mass lost during their RGB ascent (e.g., [14, 43, 29, 78]). Thus, depending on the total mass loss, RGB stars of a given chemical composition can become cool red HB stars, very hot (and thus UV-bright) extended (or extreme) HB (EHB) stars ([36]) – or a whole "rainbow" of intermediate options, including the RR Lyrae (pulsating) stars and the regular (A- and B-type) blue HB stars. Blue subdwarf (sdB) stars have long been identified as the field counterparts of the EHB stars that are found in globular clusters ([36]). EHB status may also characterize at least some among the cooler O-type subdwarf (sdO) stars, whereas other sdO's likely represent the progeny of EHB stars ([39]). Among the UV-bright progeny of hot HB stars one also finds the so-called "asymptotic giant branch (AGB) manquè" stars ([35]) and the "post-early AGB" stars ([5]), whose evolutionary properties are further described in [28, 16].

In general, for a given chemical composition, larger amounts of mass loss lead to bluer positions on the ZAHB, and thus to more efficient far-UV emitters. In fact, even beyond the EHB proper there may still be "life" on the HB phase: as recently discussed by several authors, the RGB progenitors of HB stars may (somehow) lose so much mass prior to arriving on the ZAHB that they may miss the helium "flash" at the RGB tip altogether, but still ignite helium during the white dwarf cooling curve (e.g., [8, 13]). Such "late flashers" are predicted to be even hotter than EHB stars, and have quite anomalous surface abundances compared to EHB stars (see, e.g., [60, 61, 49]). In the observed color-magnitude diagrams (CMD's) of Galactic globular clusters, such stars have been identified as the "blue hook" feature that is seen towards the very hot end of blue HB "tails" (e.g., [21, 22, 87, 79, 77]).

For a given chemical composition, bolometric luminosity is roughly constant along the ZAHB. Therefore, the hotter a star becomes when it reaches the ZAHB, the higher its potential contribution to the population's total UV output. As a consequence, in order to be able to reliably predict the UV light emanating from a given stellar population that may contain HB stars (i.e., in which a sufficiently old component is present), one must be able to reliably predict the distribution of temperatures along the HB.

This is far from being a trivial task. Such a temperature distribution, for a given chemical composition, is mainly determined by mass loss on the RGB (in addition to age). Therefore, one must accordingly be able to reliably compute mass loss rates (and how they vary with time) for RGB stars in order to be able to predict the UV colors of such a stellar population.

In addition to mass loss and age effects, both theoretical and empirical evidence reveals that the temperature of a star along the HB depends on its chemical composition, as indicated by its metallicity Z and helium abundance Y. The former plays the well-known role of "first parameter" in the determination of HB morphology, whereas the latter, which was the first suggested "second parameter," has recently regained popularity as a second-parameter candidate (see [17] for a recent review). In short, HB type tends to become redder with increasing Z, whereas it tends to become bluer with increasing

Y. Therefore, in order to be able to reliably predict the UV output from an old stellar population, one needs not only accurate mass loss rates, but also to know the variation in the helium abundance with metallicity.

From these basic conclusions to the scenarii in which very old, metal-poor stellar populations (e.g., [52, 69]), or old, metal-rich, but very helium-enriched populations (e.g., [27]), are responsible for the UV upturn in the observed spectra of elliptical galaxies and bulges of spirals (see the several excellent reviews in this volume) is just a fairly immediate logical step. Evidence in favor of the high-metallicity scenario is provided by the presence of EHB stars in high-Z *open* clusters, including the ~ 7 Gyr-old ([81]) NGC 188 ([48]) and the ~ 8 Gyr-old ([12]) NGC 6791 ([46, 45, 48, 9, 12, 33]). Both of these clusters are well known for their supersolar metallicities (e.g., [89]).

It is at present quite well established that the UV upturn is indeed due to hot HB stars and their progeny (e.g., [35, 68, 6, 73]). Direct confirmation that such stars are present in the cores of elliptical galaxies, and thus are most likely responsible for the UV upturn phenomenon, has been provided by the deep *Hubble Space Telescope* near-UV STIS images of the nearby elliptical galaxy M32 (see [7]). In addition, such stars have also been found in our own Galactic bulge ([3, 10]). Therefore, if viewed from an outside galaxy, our own Milky Way's bulge would also present a UV upturn – and it would be caused by the presence of EHB stars (and their progeny).

The main question that remains unanswered, therefore, is: *what is the physical origin of these hot HB stars?* In other words, is the UV upturn phenomenon due to very old, metal-poor stellar populations, or is it due instead to highly helium-enriched metal-rich populations? A third possibility is that binary star evolution is the actual culprit, as recently discussed by [37] (see also Sect. 4 for further discussion). In this review, our main goal is not to provide a solution to this long-standing problem. Instead, we shall focus on some key ingredients that, in our view, must be better treated in the theoretical models if we ever wish to be able to obtain convincing predictions of the UV output of a given (old) population. While our main focus is on single-star evolution, the caveats we raise should also be of relevance in the case of binaries.

2 The Helium Enrichment "Law" in Different Stellar Populations

It is now very well established that, even within one individual galaxy, different stellar populations follow different chemical enrichment "laws," as indicated by the measured abundances of the so-called α-capture (including Ne, Mg, Si, S, Ca, Ti), $r-$process (e.g., Rh, Ag, Eu, Pt), and $s-$process (e.g., Sr, Zr, Ba, La) elements. This becomes particularly evident when analyzing their respective trends with [Fe/H] (e.g., [86, 71]).

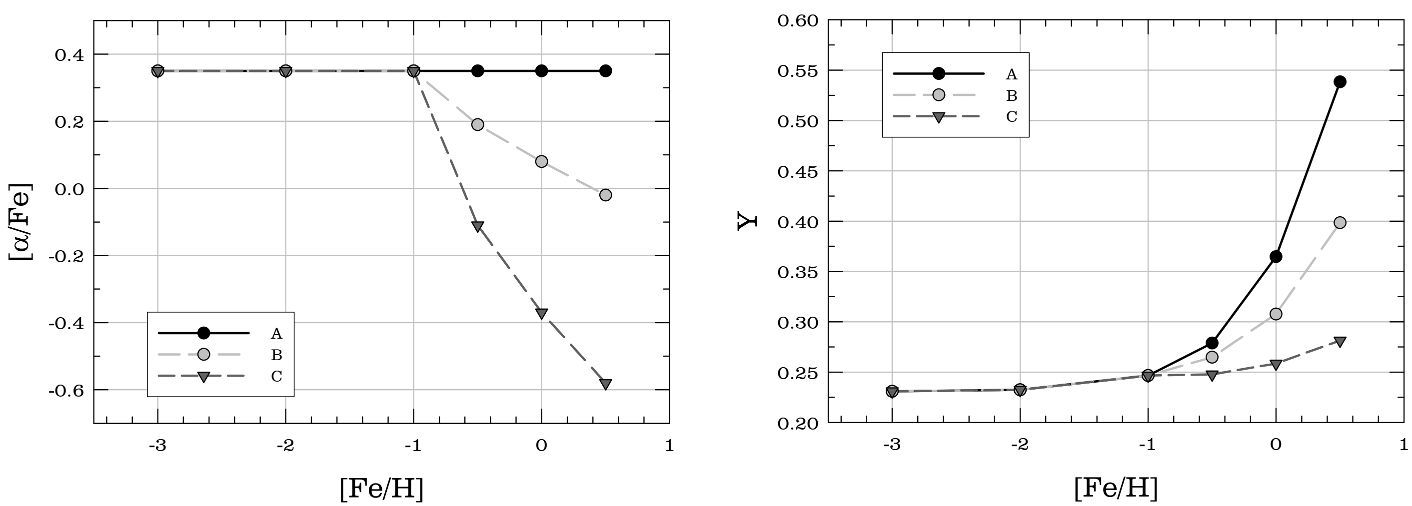


Fig. 1. The results of simple chemical evolution models ([19]) are shown in the $[\alpha/\mathrm{Fe}] - [\mathrm{Fe/H}]$ plane (*left*) and in the corresponding helium abundance $Y - [\mathrm{Fe/H}]$ plane (*right*) for three different scenarios regarding the maximum relative fraction of SN Ia events: 0% (Case A), 10% (Case B), 40% (Case C). As can clearly be seen, high-metallicity stellar populations with a strong level of α-element enhancement are expected to be strongly enriched in helium as well.

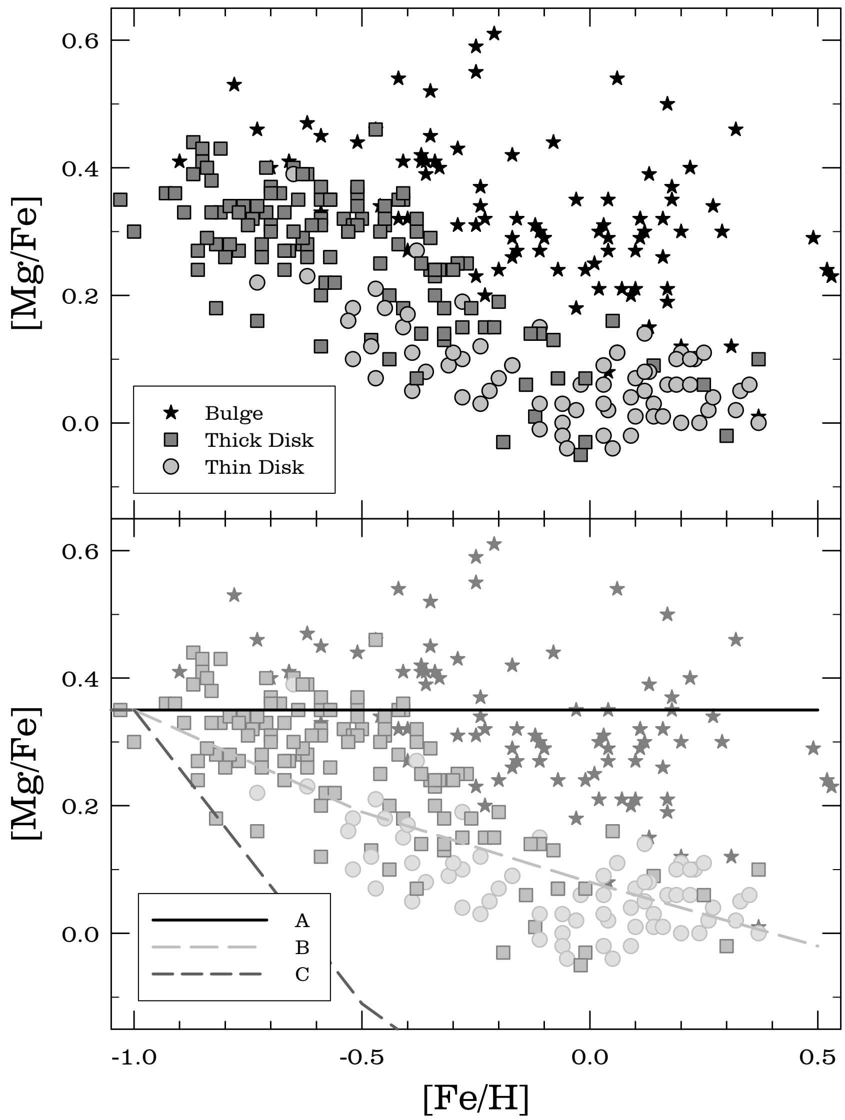


Fig. 2. *Upper panel:* Observed Mg abundances (taken as representative of the abundances of the α-capture elements) as a function of [Fe/H] for Galactic bulge (*star symbols*), thick disk (*squares*), and thin disk (*circles*) stars. As can clearly be seen, bulge stars are enhanced in Mg relative to disk stars. *Lower panel:* same as in the upper panel, but with the chemical evolution models shown in Figure 1 overplotted. "Case A" models, in which SN II play the most important role, provide a better description of the bulge stars than do the other chemical enrichment scenarios, thus implying a large helium enhancement in high-metallicity bulge stars (see the right panel in Figure 1) as compared to disk stars with similar [Fe/H].

Recently, it has become particularly clear that the Galactic bulge follows a different enrichment law than does the Galactic thick disk, which in turn follows a different law from the thin disk (e.g., [91, 23, 1, 50, 31, 76]). As pointed out by several of the quoted authors, the overabundance in at least some of the α-capture elements up to high metallicities for the bulge stars likely indicates a very short formation timescale for the Galactic bulge, whose chemical enrichment seems accordingly to have been dominated by ejecta from type II supernova (SN II) explosions. In like vein, (massive) elliptical galaxies also appear to be characterized by high metallicities and supersolar α-to-iron ratios (e.g., [88, 25, 83, 34, 56, 57]).

What is the relation between these well-known trends and the production of hot HB stars in galaxies? Here we would like to emphasize the often overlooked fact that different α-enrichment trends with [Fe/H] are also expected to be accompained by different trends in the helium enrichment "law" with [Fe/H]. This is clearly shown in Figure 1, which is based on the simple chemical evolution calculations carried out by [19], in which the contribution of type Ia supernovae (SN Ia) to the chemical enrichment is assumed to increase with [Fe/H] above $[\mathrm{Fe/H}] = -1.0$, and to be negligible for lower metallicities. In Case B, the relative number of SN Ia events reaches a maximum of 10%, whereas in Case C a maximum of 40% of SN Ia events is assumed. Case A assumes the contribution of SN Ia to be negligible even at high metallicities. As can clearly be seen, the variation in the helium abundance with [Fe/H] depends very strongly on the relative contributions of different types of supernovae to the chemical enrichment of a stellar population. In other words, different $[\alpha/\mathrm{Fe}] - [\mathrm{Fe/H}]$ curves imply different $Y - [\mathrm{Fe/H}]$ curves as well – and this *must* be accounted for in the detailed modelling of α-enhanced, high-metallicity stellar populations, such as appears to be the case in elliptical galaxies and the bulges of spirals.

Figure 2 (*upper panel*) shows the available Mg-to-Fe abundance ratios for Galactic bulge stars (*star symbols*), compared to similar data for Galactic thick (*squares*) and thin (*circles*) disk stars. Data for bulge stars were taken from the studies by [1, 50, 76], which were complemented with data for disk stars from [2, 72]. This plot clearly confirms the already well-known differences in α-enhancement behavior for the different metal-rich Galactic components. The *lower panel* in Figure 2 overplots the models by [19] previously shown in Figure 1 on these data. This plot clearly indicates that a high contribution of SN II is needed to explain the high α-enhancement levels observed among bulge stars. Figure 1, in turn, reveals that such a high SN II contribution also implies that high-metallicity stars in the Galactic bulge are likely to be He-enhanced compared to disk stars with similar [Fe/H], by an amount which can reach almost $\Delta Y_{\mathrm{bulge-disk}} \approx 0.15$ at $[\mathrm{Fe/H}] = +0.5$.

As a consequence, such a high level of α-enrichment can have very important consequences for the production of extremely hot HB stars in elliptical galaxies and the bulges of spirals. As shown by several different authors, including [40, 4, 27, 90], for the observed UV upturn in the observed spec-

tra of these galaxies to be successfully accounted for in terms of single-star, high-metallicity evolutionary models, one needs a very high level of helium enrichment. The available spectroscopic evidence, by pointing towards high α-enrichment levels being present in these galaxies, may provide a natural explanation for the required (high) helium abundances. In any case, we caution that a reliable, quantitative assessment of the level of helium enrichment to be expected in different populations associated with galaxies of different Hubble types will require considerable progress to be achieved in the modelling of the yields of high-mass stars, the shape of the initial mass function (especially at its high-mass end), and in our understanding of the very origin and formation history of these galaxies (e.g., [1, 31, 54]).

3 The Mass Loss "Law" for RGB Stars

The amount of mass lost by an RGB star is crucial in determining the temperature such a star will end up with when it reaches the ZAHB (e.g., [78, 28]). In particular, in order to become EHB stars, the progenitors of HB stars must lose large amounts of mass during the RGB phase. Therefore, in order to reliably predict the UV output from a stellar population, reliable mass loss rates for low-mass RGB stars are required.

Unfortunately, we remain unable at present to compute reliable mass loss rates for red giants, either from detailed theoretical models based on first physical principles – which are still lacking in the literature – or from semi-empirical recipes based on observational material.

This is not to mean that such semi-empirical recipes are also lacking; quite the contrary, in fact: as discussed in [15, 17], there exist at present several different such recipes which are equally satisfactory at describing the available mass loss rates for red giant stars. Some such recipes are given in Figure 3 (see the Appendix in [15] for more details). All these formulae are based on original expressions suggested by the indicated authors; thus "modified Reimers" is reminiscent of the original Reimers mass loss formula ([74, 75]), but allowing the exponent on the right-hand side of the equation to be determined by the data, as opposed to being imposed a priori. The other expressions also have exponents determined by least-squares fits to the data – and these exponents generally differ somewhat from the originally proposed ones (for the Mullan expression, see [66]; Goldberg's recipe appears in [32]; Judge & Stencel's is given in [44]; finally, the VandenBerg expression appears first in [15]).

What is especially important to note here is that these expressions, though all roughly equivalent in their capacity to describe the available mass loss data ([15]), imply integrated mass loss values that differ from one case to the next, thus also implying different metallicity and age dependencies (see also [15, 17]). This is more clearly shown in Figure 4: in the *upper panel*, one sees the different metallicity dependencies for a fixed age (9 Gyr), with the absolute integrated mass loss values having been normalized to $0.10\,M_{\odot}$ at

$$\dot{M} \propto \left(\frac{L}{g\,R}\right)^{+1.4} \qquad \text{(modified Reimers)}$$

$$\dot{M} \propto \left(\frac{g}{R^{3/2}}\right)^{-0.9} \qquad \text{(Mullan)}$$

$$\dot{M} \propto R^{+3.2} \qquad \text{(Goldberg)}$$

$$\dot{M} \propto g^{-1.6} \qquad \text{(Judge-Stencel)}$$

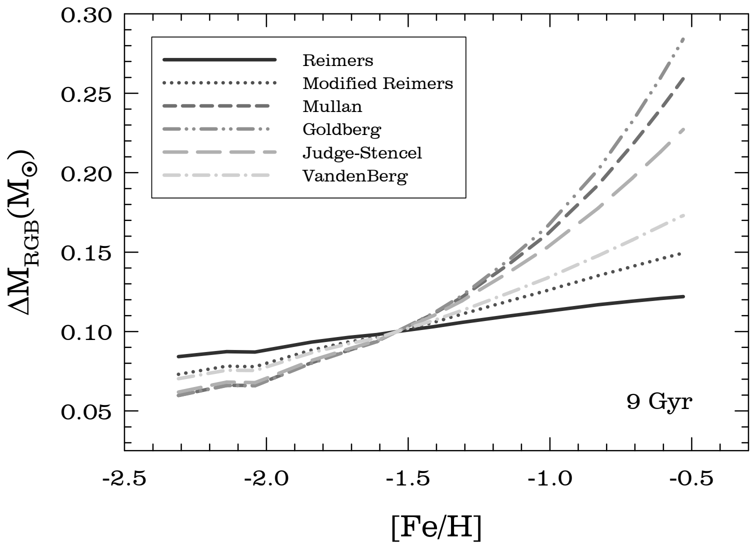
$$\dot{M} \propto L^{+1.1} g^{-0.9} \qquad \text{(VandenBerg)}$$

Fig. 3. Mass loss "laws" for red giant stars. As shown in [15], all these expressions are equally successful in accounting for the available (measured) mass loss rates for red giants. By contrast, the original Reimers formula ([74, 75]) is unable to describe the available empirical data.

[Fe/H] $= -1.5$; likewise, the *lower panel* shows the different age dependencies at a fixed metallicity ([Fe/H] $= -0.71$), where the absolute integrated mass loss values have been normalized to $0.20\,M_{\odot}$ for an age of 12 Gyr. These plots show very clearly that most of the available recipes predict both a metallicity and an age dependence that are *stronger* than in the case of the commonly adopted Reimers "law" – the only exception being, in fact, the milder age dependence predicted by the Goldberg expression.

Unfortunately, until we are in a position to reliably decide which of these several expressions (if any; see [15, 17] for several lingering caveats) provides a better description of the available data, we will remain fundamentally unable to reliably predict the UV output from a given stellar population. A safer approach at present would likely be to analyze independently the impact of each of these recipes upon the model predictions – which should give us a better handle of the systematic errors that are brought about by our lack of a unique, reliable description of mass loss rates in red giant stars.

The (future) availability of such a description notwithstanding, the empirical evidence strongly suggests that mass loss would *still* retain a stochastic component, as indicated by the spread in colors that is *always* present in the observed CMD's of globular clusters, and which reveals the presence of a spread in mass loss rates at the (typical) level of $\sigma_M \simeq 0.02 - 0.03\,M_{\odot}$ (e.g., [78, 51, 26, 85]). The existence of such a spread in mass loss is obviously very important in order for reliable predictions of the UV output from a given stellar population to be obtained, since it is precisely those stars at the high-ΔM tail of the mass loss distribution that will end up at hotter positions on the ZAHB, and thus produce the higher amount of UV light. In fact, the presence



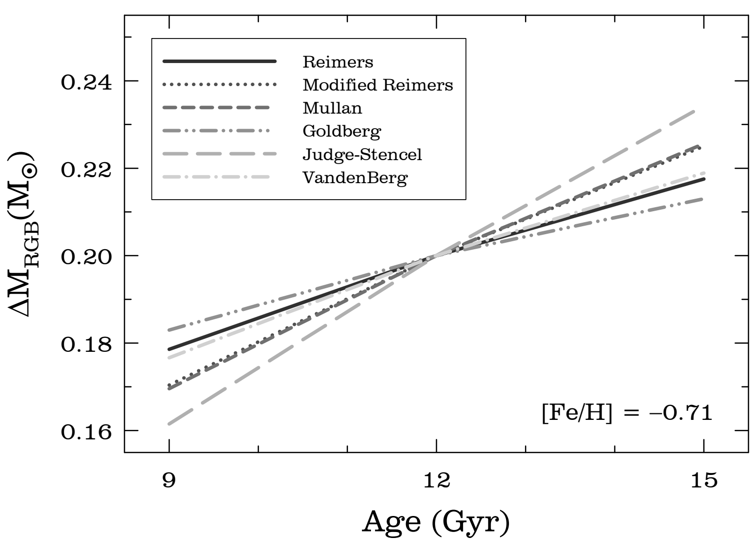


Fig. 4. Integrated RGB mass loss variation with [Fe/H] at an age of 9 Gyr (*upper panel*) and with age at a fixed [Fe/H] = -0.71 (*lower panel*). In the upper panel, mass loss has been normalized to a value of 0.10 $M_\odot$ at [Fe/H] = -1.5, whereas in the lower panel the normalization condition specifies an integrated mass loss of 0.20 $M_\odot$ at 12 Gyr. The different lines in these plots indicate the predicted (integrated) RGB mass loss for the several different mass loss recipes provided in Figure 3, and also for the original Reimers ([74, 75]) expression. Note that the mass loss variation with both metallicity and age depends on the adopted recipe for $\dot{M}$.

of spectroscopically confirmed ([59]) hot blue HB stars in such famous *red* HB clusters as 47 Tucanae (NGC 104) and NGC 362 is proof of the importance of quantitatively establishing the spread in mass loss rates in order to determine the number of UV contributors in a given stellar population.

In this sense, while it has been suggested that such a dispersion in mass loss may be related to the central density of stellar systems, and hence most likely to dynamical effects ([18]), a systematic study is still lacking, and is further complicated by the discovery of multiple stellar components with different levels of helium enrichment in several among the most massive Galactic globulars (e.g., [11, 70] and references therein).

One way or another, it remains unclear at present the level to which stochastic spreads in the integrated mass loss should be adopted in models of elliptical galaxies and the bulges of spirals. In fact, the suggested dependence on central density for Galactic globular clusters ([18]) may point towards a smaller spread in mass loss in the field populations of galaxies than is seen in high-density globulars.

4 Different Channels for EHB Stars in the Field vs. Clusters?

It has recently been shown ([64, 63, 62]) that (close) binary systems are not present in significant numbers among the hottest HB stars in Galactic globular clusters. In this sense, [62] estimate a most likely (close) binary fraction $f = 4\%$ among EHB stars in NGC 6752, to be compared with an estimated $f = 42 - 69\%$ among field sdB stars ([55, 67, 65]; see also [38, 37] for additional references to field star work).

This may point to different evolutionary channels for the production of EHB stars in globular clusters and the field. If so, the usual approach of using observations of resolved globular clusters as a guide to the physical origin of the UV upturn phenomenon affecting elliptical galaxies and spiral bulges may in fact be quite inadequate. Note that [62] suggest that the different f fractions between field and globular cluster stars may be due to an $f-$age relation, with the field systems being on average significantly younger than those found in globulars.

In fact, it is not unlikely that the primordial binary fraction in globular clusters is quite low. The CMD study by [20] shows that the main-sequence binary fraction is small away from the center in NGC 6752, whereas *Hubble Space Telescope* data suggest that it is in the $15 - 38\%$ range closer to the core ([80]). According to the realistic N-body simulations by [42], one expects the primordial binary frequency of a cluster to be well preserved outside the cluster's half-mass radius, thus supporting a small primordial binary fraction in NGC 6752, in line with the EHB results by [64, 63, 62]. A similar result was obtained very recently in the case of NGC 6397 (H. Richer, *priv. comm.*). Intriguingly, [47] has very recently argued against a high primordial binary

fraction among *field* stars as well, pointing out that $\sim 2/3$ of all main-sequence stellar systems in the Galactic disk appear to be single, and arguing that the most common outcome of the star formation process is a single rather than a multiple star. One way or another, the seemingly high primordial binary fraction for field sdB stars does give some support to the scenario in which binaries play a relevant role in explaining the UV upturn phenomenon ([37]).

5 Conclusions

The UV upturn (or UVX) phenomenon affecting elliptical galaxies and the bulges of spirals remains at present one of the most intriguing problems encountered at the interface between stellar and extragalactic astronomy. While it appears clear that the stars responsible for the observed far-UV light are the so-called EHB stars (and their progeny), it is not clear in detail how these stars are produced. This has given rise to several different proposed explanations for the detected upturn in the observed far-UV spectra, including the "low metallicity, very old ages" scenario (e.g., [52, 69]), the "high metallicity, high helium abundances" scenario (e.g., [40, 4, 90]), and the binary stars scenario ([37]). Whatever one's favorite theoretical framework, reliable predictions cannot be obtained without adequate knowledge of the underlying variation in the helium abundance with metallicity and in the integrated RGB mass loss with both metallicity and age.

Concerning the helium enrichment "law," we have argued that the available spectroscopic data for Galactic field stars, which indicate different α-capture enrichment laws for different stellar populations (bulge, thick disk, thin disk), also imply different *helium abundance* trends with [Fe/H], the resulting differences in Y (at fixed [Fe/H]) potentially reaching very significant levels (i.e., $\Delta Y_{\rm bulge-disk} > 0.1$) at supersolar [Fe/H]. Therefore, in the high metallicity scenario, it should be easier to produce EHB stars for a bulge chemical enrichment law than if one assumes a "universal," disk-like "law" to apply for different stellar populations in galaxies of different Hubble types.

Hot HB stars would not exist if their immediate progenitors, namely low-mass RGB stars, did not lose substantial amounts of mass prior to arriving on the ZAHB. Unfortunately, we remain fundamentally unable to predict the amount of mass that a given RGB star will lose as it climbs up the RGB, due both to the lack of suitable theoretical models and to insufficient observational data constraining the phenomenon. While the original semi-empirical mass loss formula by Reimers ([74, 75]) has been shown to be inconsistent with more recently derived mass loss rates, several alternative formulations have been proposed which can all account for the more modern observational data equally satisfactorily. This limits the extent to which we can build predictive models of the UV upturn phenomenon, since each of the available mass loss recipes predicts a different mass loss dependence on metallicity and age. An important breakthrough in our understanding of mass loss rates in red giants

will be needed before we are in a position to conclusively corroborate the proposed scenarios for the origin of the UV upturn phenomenon.

EHB stars in globular clusters have long been used to gain insight into the origin of the UV upturn phenomenon. However, the current evidence appears to increasingly point to different formation channels for field and cluster EHB stars – in particular, the binary fraction of field sdB stars appears to be very high, whereas (close) binary systems seem to be lacking in globular clusters. If confirmed by more extensive observations (only a couple of globular clusters have been adequately monitored so far), it may not be entirely appropriate anymore to rely on observations of resolved globulars to gain insight into the physical origin of the UV upturn phenomenon affecting elliptical galaxies and the bulges of spirals. Indeed, the evolutionary channels producing EHB stars, and hence the observed far-UV flux, may be quite different in the field and in clusters, binary stars plausibly playing a more important role in the case of the former.

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